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Natural Hydrogen: A Mini-Review Unveiling Its Potential as a Key to Sustainable Future for Energy

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ABSTRACT

As the global energy shortage challenge and transition continues, greater attention is being drawn to natural hydrogen, a clean and high-potential energy source. This review aims to provide an overview about the formation mechanism, exploration technology, research status of revolutionary natural hydrogen, as well as its key role and potential impact in achieving a sustainable future for energy. Natural hydrogen is produced primarily through serpentinization, a process in which water reacts with iron-rich ultrabasic rocks and is hypothesized to have the potential for forming gas accumulations in certain suitable regions of the world. Although natural hydrogen reserves are presently unclear, it is a promising solution to accelerate the decarbonization of energy-intensive industries. Until now, numerous studies have been conducted in many countries and regions, leading to multiple ambitious projects (currently under construction or implementation) and demonstrating the feasibility of using existing technologies for the safe exploration of natural hydrogen. With the development of natural hydrogen, it is believed that more resources will be certainly found and the remaining issues could be resolved in the future. This work could offer important insights for the development of natural hydrogen that is a key toward a sustainable future of energy.

1 | Introduction

The idea of a sustainable energy future revolves around establishing a system that fulfills present societal demands without compromising the capacity of future generations to satisfy their own needs. This entails the utilization of clean renewable resources such as solar, wind, and natural hydrogen, alongside enhancing energy efficiency and reducing environmental damage (more discussions can be found in Supporting Information S1) [1]. These low-carbon energy solutions are key to addressing climate change, safeguarding the environment, alleviating energy shortages, and ensuring economic growth [2, 3].

Natural hydrogen, a carbon-free energy source, is attracting increasing attention worldwide [4, 5]. Natural hydrogen offers several advantages over hydrogen production through water

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electrolysis and methane reforming: (1) fewer greenhouse gas emissions during its production and extraction; (2) potential cost advantages as it eliminates the need for large-scale hydrogen production equipment (though equipment for extraction or separation may still be required); (3) lower overall energy consumption compared to artificial production methods, as it avoids the high energy input required for processes such as electrolysis or reforming (though energy may still be needed for extraction or related operations). Notably, green hydrogen (produced using renewable-powered electrolysis) is constrained by high costs and energy intermittency, whereas blue hydrogen (fossil fuel-derived with CO_2 capture) remains roughly twice as expensive as gray hydrogen, further highlighting the competitiveness of natural hydrogen. It is formed by deep geological processes, including water rock reactions, deep earth degassing, and water radiolysis, and represents a key branch of the hydrogen field, with a wide application potential and the potential to become the cornerstone of the future energy transition [6]. Countries and regions around the world have engaged in research and development into natural hydrogen: it is commercially mined in Mali, Africa; highly concentrated reserves are found in the French Lorraine basin; exploration wells in the islands and peninsulas of Australia have revealed significant quantities; and China has geological conditions favorable to exploration [7]. Meanwhile, governments across more countries are ramping up funding investment in the natural hydrogen sector to accelerate its research and industrialization.

The environmental significance of natural hydrogen stems from its capacity as a clean energy resource, though its sustainability remains a topic requiring nuanced discussion because continental systems lack a regenerative cycle on the decadal-to-centennial timescales relevant to human energy use. Nevertheless, utilizing it can yield favorable ecological effects, including the reduction of greenhouse gas emissions, enhancement of the reliability of energy supply chains, and improvement of energy independence and security. When combusted, hydrogen fuel emits solely water vapor, without releasing carbon dioxide or other detrimental pollutants—an attribute that aids in mitigating climate change and enhancing air quality [8].

Despite its advantages, natural hydrogen faces significant challenges, especially in the field of transport. But if existing oil and gas transport technologies can be adapted to safe natural gas-based transportation, it could be a game changer, much as oil was in the 19th century oil boom. Global cooperation could unlock its potential and offer a zero-carbon long-term viable energy option for future generations. In addition to its direct applications, the development of natural hydrogen could stimulate technological innovation, cost reduction, efficiency improvement and sustainable development, thereby promoting a greener planet. To provide a concise overview of this promising energy source, this review focuses on four core scopes: first, its formation mechanism; second, key exploration technologies; third, global research status and practical projects; and finally, its role in addressing global energy shortages, advancing energy transition and decarbonization, with the aim of offering insights for its future development.

2 | Natural Hydrogen

2.1 | Formation Mechanism

Natural hydrogen has emerged as a promising and long-term viable energy source, captivating the attention of researchers and industries alike. Given its significance, understanding how it comes into existence is crucial. Natural hydrogen is generated through several mechanisms, which include abiotic factors such as crustal radiation that disassociates water and deep degassing, as well as possible biological causes. The primary mechanisms responsible for this phenomenon are serpentinization and water radiolysis [9]. Many of these processes occur deep underground, where hydrogen rises to the surface through plate boundaries and fault fissures, though not all do. Radiolysis, for instance, does not inherently require deep subsurface temperatures or pressure. The main natural hydrogen formation mechanisms are shown in Figure 1.

2.1.1 | Serpentinization

Serpentinization is a remarkable abiotic process of natural hydrogen formation, and stands as the predominant type of H_2 source generated by water–rock interactions during the Phanerozoic [15]. At temperatures typically ranging from 200°C to 350°C, mafic minerals in basic and ultrabasic rocks, such as peridotite (an ultramafic rock dominated by olivine, including its end-members forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), and orthopyroxene, including enstatite ($MgSiO_3$) and ferrosilite ($FeSiO_3$)), undergo serpentinization. As extensively reported in the literature (e.g., ref. [16] and ref. [15]), this process—a hydration and oxidation reaction often classified as low-temperature metamorphism or metasomatism (though not exclusively hydrothermal)—produces serpentine ($(Mg/Fe/Ni)_6Si_4O_{10}(OH)_8$) alongside other minerals such as brucite ($Mg(OH)_2$), talc ($Mg_3Si_4O_{10}(OH)_2$), and magnetite (Fe_3O_4), with concurrent hydrogen generation. Herein “low-temperature” is relative to high-temperature geological processes such as magmatism or high-grade metamorphism. The factors affecting the serpentinization process include, but not limited to, temperature, redox degree, pH, and water–rock ratio [17]. These factors collectively regulate the extent and product of serpentinization. For example, both temperature and the water–rock ratio strongly influence the extent of serpentinization and the chemical composition of the resulting fluids, which in turn affects hydrogen generation and mineral assemblages [18].

A key aspect of serpentinization is the generation of hydrogen, which occurs through the oxidation of the ferrous component (Fe^{2+}) in olivine and orthopyroxene to ferric iron (Fe^{3+}), as shown in Equation (1):

$$2FeO + H_2O \rightarrow Fe_2O_3 + H_2\,(aq) \tag{1}$$

Here, “FeO” in the reaction is a simplified representation for Fe^{2+}-bearing minerals (e.g., the olivine and orthopyroxene mentioned above), and “Fe_2O_3” denotes the oxidized Fe^{3+}-bearing phase.

FIGURE 1 | Main natural hydrogen formation mechanisms. Herein, mantle degassing, which was historically considered a plausible mechanism for natural hydrogen production, is no longer included, as it has been ruled out by Ballentine et al. in their 2025 review article [10]. Magma degassing can occur in both the lower and upper mantles. Insets (clockwise from top right) are adapted from ref. [11] with permission (Copyright 2021, American Chemical Society), ref. [12] with permission (Copyright 2020, The Author(s), under exclusive license to Springer Nature Limited), ref. [13] with permission (Copyright 2023, American Chemical Society), and ref. [14] with permission (Copyright 2020, The Author(s), under exclusive license to Springer Nature Limited), respectively. The magma degassing inset at the 9 o'clock position is created by the authors, while the rock inset is from public domain and no permission is required.

This process often occurs near Earth's plate boundaries, such as mid-ocean ridges, deep fractures of transitional faults, convergent plate boundaries, and deep piles of layered igneous rock intrusions. However, to date, no proved gas reservoirs formed through this process have been identified globally. Instead, most natural hydrogen, including in Mali, occurs in aqueous form [19]. Generally speaking, serpentinization plays a crucial role in the Earth's water and carbon cycles, significantly impacting processes occurring both on the surface and within the Earth's depths [20].

2.1.2 | Radiolysis of Water

The radiolysis of water in nature is a complex process involving multiple sequential reactions, driven by high-energy radiation, such as cosmic rays and alpha (α), beta (β), and gamma (γ) rays from natural radioactive decay [9, 21, 22]. Geologically, this process occurs in settings where radioelements are ubiquitous in the upper crust [10]. They have higher concentrations in igneous and felsic metamorphic rocks, as well as in sedimentary systems, where trace elements can be concentrated by secondary fluid migration and precipitation. This distribution makes radiolysis a substantial H_2 source, particularly in Precambrian terranes, U-enriched terranes, deep-sea sediments, and fractured basalts. A commonly accepted overall reaction summarizes its net effect [5, 10]:

$$2H_2O \xrightarrow{\text{ionizing radiation}} H_2 + H_2O_2 \tag{2}$$

This global equation encapsulates the ultimate decomposition of water into hydrogen (H_2) and hydrogen peroxide (H_2O_2), arising from a series of intermediate radical reactions involving transient species such as solvated electrons ($e^-(aq)$), hydrogen radicals ($H\cdot$), and hydroxyl radicals ($OH\cdot$).

For α particles, their interaction with water does not occur through a single direct chemical step. Instead, their high ionizing power initiates the sequence of reactions underlying the overall process shown in Equation (2), driving the formation of the net products through cascading radical intermediates.

For β rays (high-energy electrons), the primary interaction with water begins with ionization, followed by radical formation (Equations (3–5)):

$$H_2O \rightarrow H_2O^+ + e^- \tag{3}$$

$$e^- + H_2O \rightarrow e^-(aq) \tag{4}$$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH\cdot \tag{5}$$

These steps reflect the initial generation of charged species and radicals, which further react to contribute to the overall radiolytic decomposition. Additionally, β rays can excite water molecules without ionization, a process that also feeds into the broader sequence of radiolytic reactions.

For γ rays interacting with H_2O, γ rays typically interact with H_2O molecules through processes such as the photoelectric effect, Compton scattering, or electron pair formation, rather than directly causing ionization. However, γ rays can lead to the excitation of H_2O molecules and the formation of free radicals. The reactions are complex and cannot be easily expressed in simple equations.

Ionization of H_2O molecules:

$$H_2O + \gamma \rightarrow H_2O^+ + e^- \tag{6}$$

or

$$H_2O + \gamma \rightarrow H^+ + OH^- \tag{7}$$

Excitation of H_2O molecules:

$$H_2O + \gamma \rightarrow H_2O^* \tag{8}$$

The energized water molecule (H_2O*) has several pathways to return to its ground state, which may involve processes such as fluorescence or the release of heat.

Reduction of H_2O molecules to H_2:

$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^- \tag{9}$$

The radiolysis process of H_2O is also affected by temperature and the chemical composition of aqueous system (or the impurities/dissolved substances in H_2O). For instance, water solutions containing copper ions exhibit varying decomposition behaviors when exposed to radiation. Specifically, the presence of Cu^{2+} ions could facilitate the production of H_2O_2 and H_2, while having minimal impact on the generation of O_2 [23].

In nature, radiolysis of water can have a significant impact on the environment. For example, it can alter local redox conditions and affect the mobility of metals, subsequently impacting the environmental chemistry [22]. The radiolysis of water additionally plays a crucial role in the safety of nuclear waste management within geological disposal [24]. The byproducts of this decomposition can influence both the corrosion rate of the metal containers used for nuclear waste and the solubility of the solidified waste matrix. Overall, radiolysis of water is a complex process with multiple steps and products that are crucial for understanding radiation–matter interactions [25, 26].

2.1.3 | Biological Processes

Although biological processes are generally considered a less dominant source of natural hydrogen compared to abiotic pathways such as serpentinization, examining them remains relevant for a holistic understanding of the full range of natural hydrogen formation mechanisms. The mechanism of natural hydrogen formation through biological processes in nature mainly involves microbial activities. These microorganisms produce hydrogen during their metabolism through fermentation and nitrogen fixation reactions [17] Certain microorganisms, including specific bacteria, archaea, and cyanobacteria, possess the ability to either generate hydrogen or utilize it as an energy source due to the presence of hydrogenase within their cellular structures. Hydrogenase can catalyze the reversible redox reaction of H_2, that is, the oxidation of H_2 to protons and electrons or the reduction of protons to H_2 (Equations (10 and 11)) [27].

H_2 is oxidized to give protons and electrons:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{10}$$

This reaction represents the oxidation of H_2 molecules into protons and electrons catalyzed by hydrogenase.

Proton reduction to H_2:

$$2H^+ + 2e^- \rightarrow H_2\uparrow \tag{11}$$

This reaction refers to the combination of protons and electrons to form H_2, which is also catalyzed by hydrogenase.

Biological processes in nature predominantly generate natural hydrogen through the metabolic functions of microorganisms capable of utilizing or producing hydrogen, with hydrogenase serving a crucial catalytic function in this mechanism [28]. However, this biological production route is often hampered by slow reaction kinetics, which limit the efficiency and scalability of hydrogen generation [29]. Additionally, the complex and delicate nature of the microbial environments required for these processes makes them highly sensitive to changes in temperature, pH, and the presence of contaminants, further complicating large-scale implementation.

2.1.4 | Mantle Degassing

Mantle degassing, historically considered a plausible mechanism for natural hydrogen production due to its association with mantle-derived fluid release, warrants brief mention despite being excluded from the current framework. This mechanism, which posits hydrogen release during mantle convection or magma ascent, was once debated as a potential source of natural hydrogen reservoirs. However, as noted in Figure 1, it has been ruled out by Ballentine et al. in their review article in year 2025 [10], based on cumulative evidence challenging its relevance to significant natural hydrogen accumulations. Nonetheless, we retain this brief discussion to provide context: understanding historical hypotheses, even those now discounted, helps frame the evolution of research in natural hydrogen genesis. The principle of natural hydrogen formation through mantle degassing is based on the complex process of the Earth's deep geological structure. The Earth's mantle represents the most significant internal layer of the planet, comprising materials that contain a specific quantity of hydrogen, which exists under conditions of elevated temperature and pressure. Under certain geological conditions such as mantle convection, plate subduction, or lithospheric extension, mantle materials undergo partial melting or metamorphism, leading to the release of hydrogen and other volatile substances stored in the mantle [30].

The formation and release of natural hydrogen gas in the Earth's interior is shown in Figure 2. Figure 2a illustrates the primordial nebular atmosphere of the early Earth, characterized by magma oceans, a silicate mantle, and hydrogen present in the core predominantly as hydrogen molecules (H_2), which were incorporated into the Earth's interior through geological processes. In contrast, Figure 2b depicts the contemporary hydrogen cycle of the Earth, where hydrogen primarily exists as water (H_2O) in the atmosphere, upper mantle, and deep mantle, and potentially as hydroxide (OH^-) in the core. This indicates that mantle-degassed H_2 can be generated through various mechanisms, with detailed reaction mechanisms available in the literature [9, 31, 32].

Degassed H_2 from the mantle can migrate upward through deep and large fault zones to the crust or even the surface. The Tanlu Fault Zone serves as a significant fault system in eastern China, functioning as a crucial tectonic pathway for mantle degassing and potentially influencing the movement of mantle fluids [33]. Further, the degree of mantle degassing may also indicate the depth of the fault zone and its underlying tectonic conditions.

Degassed H_2 is linked to numerous geological and geochemical processes, such as the partial melting of mantle substances, the transfer of materials between the crust and mantle, and the movement of deep-seated fluids. These interactions culminate in the release of hydrogen gas from the Earth's mantle, which may become concentrated in certain geological settings, thereby forming natural hydrogen resources [34]. Although it has been ruled out as a key source of impactful H_2 accumulations [10], advances in exploration/utilization leave room for future understanding adjustments.

2.1.5 | Magma Degassing

Magma degassing is a proposed pathway for mantle-derived hydrogen release, though claims regarding its substantial contribution as an economic hydrogen source, as noted in ref. [10], require quantitative observational evidence to be validated. Specifically, the generation of natural hydrogen through magma degassing is fundamentally linked to magmatic processes occurring deep within the Earth [26]. As magma ascends through the Earth's crust, the decrease in pressure facilitates the release of gases, including H_2, from the magma. These gases can migrate upward using networks of fissures and fractures in the crust, ultimately reaching the surface or near-surface areas. The process of magma degassing is recognized as a significant contributor to the formation of natural hydrogen [6].

The specific principle of the formation of H_2 from magma degassing may include the following steps: [26, 35]

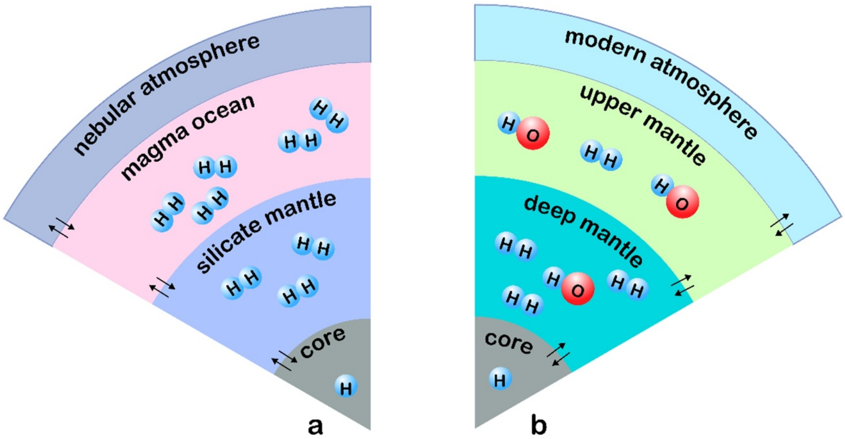

FIGURE 2 | A schematic representation of water storage is depicted in two stages: (a) during the early mantle phase characterized by the magma ocean, and (b) in the contemporary mantle (not to scale). In the early Earth, under predominantly reducing conditions, H_2 may have been allocated among various reservoirs through equilibrium partitioning. In contrast, the modern Earth, influenced by plate tectonics and mantle redox stratification, contains hydrogen in the oxidized shallow upper mantle primarily as hydroxyl groups within minerals, while considerable quantities of H_2 are likely retained in the deeper reduced mantle. Reproduced from ref. [31] with permission. Copyright 2016 European Association of Geochemistry under Creative Commons License.

1. Magma generation and rise: deep in the crust, due to mantle convection or plate tectonic activities, part of the mantle material melts to form magma. It is important to note that not all magma produced from mantle material undergoes melting.
2. Gas dissolution and storage: under the conditions of high temperature and pressure, magma can dissolve a large number of gases, including H_2 (Equations (12 and 13)) [36]. This phenomenon is crucial as the dissolved hydrogen can potentially be released under specific geological events, contributing to the natural hydrogen reservoirs in the Earth's crust [26].
   Pyrolysis dissociation of H_2O:

$$H_2O \rightarrow 2H_2 + O_2 \tag{12}$$

This reaction shows that at high temperatures, water molecules can be broken down into H_2 and O_2. In addition, some minerals in the surrounding rock may act as catalysts, facilitating the pyrolysis reaction and increasing the yield of hydrogen.
The reaction of magma to dissolve H_2:

$$H_2 + \text{Magma} \rightarrow H_2(\text{Dissolved}) \tag{13}$$

This reaction means that H_2 can be dissolved by the magma.

3. Pressure reduction and degassing: when the magma rises into the shallow part of the crust or near the surface, the pressure reduction leads to a reduction in solubility and the gas begins to be released from the magma. In other words, the gas solubility decreases as magma rises and pressures decrease.
4. Gas migration: released gases, including H_2, can migrate upward through cracks and pores in the crust.
5. Surface release: after reaching the surface, the gas (including H_2) can be released into the atmosphere through volcanic activity or fracture systems.

Furthermore, the degassed H_2 present in magma may also be associated with the reaction of water within the Earth's mantle [35, 37, 38]. Under specific geological circumstances, H_2O in the mantle interacts with rocks, resulting in the formation of H_2. The as-produced H_2 can subsequently ascend to the surface using a mechanism referred to as magma degassing. It is important to highlight that, as since most magma originates from the partial melting of mantle materials, magma degassing is a crucial component of the overall mantle degassing process.

2.1.6 | Decomposition of Hydroxyl Group in Mineral Lattice Structure

The decomposition of hydroxyl groups within mineral lattice structures to produce natural hydrogen is a chemical process that occurs under certain geological conditions, and notably, it may also be an economically important source of natural hydrogen. In some minerals, such as hydrated minerals or clay minerals, the hydroxyl groups (-OH) in the lattice can be broken down under certain conditions and release H_2. This process may include the following steps [9, 33, 39, 40]:

1. Hydroxyl groups in minerals: certain mineral structures contain hydroxyl groups, which may bind to metal ions in the mineral lattice in the form of hydrated molecules (Equation (14)).

$$M^{n+} + xH_2O \rightarrow \left[M(H_2O)_x\right]^{n+} \tag{14}$$

   where M represents metal ions, x represents the number of water molecules, and $[M(H_2O)_x]^{n+}$ represents the hydrated complex formed by metal ions and x water molecules.
2. Temperature and pressure changes: the geological environment deep underground, such as changes in temperature and pressure, can affect the stability of the mineral lattice and induce the decomposition of hydroxyl groups (Equations (15 and 16)).
   Iron oxyhydroxide (FeO(OH)) can be decomposed under high temperature and pressure conditions to produce H_2 and iron oxides:

$$2FeO(OH) \rightarrow Fe_2O_3 + H_2O + H_2 \tag{15}$$

Some H_2O-containing minerals can lose structural water at high temperatures, forming H_2 and corresponding anhydrous minerals. For example, the decomposition of serpentine at high temperatures produces H_2:

$$\text{Serpentine} + H_2O \rightarrow \text{Olivine} + 3H_2 \tag{16}$$

3. Redox reaction: in the geological environment, the hydroxyl group in the mineral lattice may participate in the redox reaction to produce H_2. For example, when minerals interact with groundwater or other fluids, redox reactions may occur, causing the hydroxyl group to be broken down to release H_2.
4. Mineral weathering: Minerals located at the surface or within shallow subterranean layers can experience weathering, and the breakdown of hydroxyl groups during this process may additionally result in the generation of H_2.
5. Microbial activity: In some cases, microbial activity may promote the decomposition of hydroxyl groups in minerals to produce H_2.
6. Geological time scales: The breakdown of hydroxyl groups within mineral lattice structures typically transpires over extensive geological time frames. Consequently, the quantity of hydrogen generated is often minimal and may necessitate particular geological conditions to reach detectable levels. Overall, the process of hydroxyl group decomposition in mineral lattice structures to yield natural hydrogen is a multifaceted geochemical phenomenon influenced by various factors, such as the mineral type, geological setting, temperature, pressure, and the mechanisms of chemical reactions.

In sum, the generation of natural hydrogen is a complex and multi-faceted process, intricately linked to a variety of geological and potentially biological mechanisms. From the slow and continuous reactions of serpentinization to the dynamic processes of water radiolysis, each mechanism plays a crucial role in contributing to the creation of this valuable energy resource. Understanding these processes not only provides insights into the natural occurrence of hydrogen but also holds the key to unlocking its potential for large-scale energy production. By further exploring these generation mechanisms, researchers can develop more effective strategies for the exploration, extraction, and utilization of natural hydrogen, ultimately paving the way for a cleaner and more sustainable future.

2.2 | Exploration Technology

As natural hydrogen gains increasing recognition as a potential game-changer in the energy landscape, the search for efficient ways to locate and assess it has become a priority. On a large scale, natural hydrogen exploration shares some similarities with fossil energy exploration in technical approaches. Commonly used technologies include remote sensing methods, geochemical analysis, geophysical techniques, and petrophysical assessments. These methods help ascertain sediment thickness above the basement, detect source rocks, and identify potential hydrogen reservoirs during exploration [7, 26, 29].

The core technologies for natural hydrogen exploration are as follows:

i. Identification of surface hydrogen seep markers [41]: remote sensing technology, which detects effects of hydrogen in soils (e.g., semicircular structures) rather than hydrogen directly, combined with surface sample collection is used to study surface hydrogen seep markers, for example, measuring gases in soils using gas analyzers.

ii. Geochemical exploration [42]: subsurface-focused geochemical exploration assesses the distribution and movement of subsurface hydrogen (and traces its source) through systematic collection and analysis of hydrogen concentrations in subsurface soil, groundwater, and formation gases.

iii. Geophysical exploration [43]: employs seismic, gravity, magnetic, and other geophysical techniques to identify subsurface structures (that can act as potential reservoirs) and faults (serving as migration pathways), thereby locating potential hydrogen reservoirs and migration pathways. These techniques are also used to locate possible sources of hydrogen like ultramafic rocks, greenstone belts, and granites among others.

iv. Drilling technology [8]: drill into subterranean rock formations and extract fluid samples to evaluate the hydrogen concentration and isotopic properties, thereby determining the origin and resource viability of hydrogen.

v. Laboratory analysis [9]: a comprehensive chemical and isotopic analysis of the gathered samples is conducted to ascertain the source and formation process of hydrogen gas.

vi. Numerical simulation [44]: employ geological models and numerical simulation methods to forecast the generation, movement, and accumulation of hydrogen.

vii. Resource assessment [45]: integrate geological, geochemical, and geophysical information to evaluate the potential occurrence and economic viability of natural hydrogen resources.

viii. Technology Development [29]: research and develop efficient hydrogen extraction, separation and storage technologies for commercial production.

Countries across the globe, including the United States, Australia, and Mali, have initiated efforts in the exploration and development of natural hydrogen [7]. Notably, Mali has successfully achieved commercial extraction of natural hydrogen, while exploration wells for this resource have been effectively drilled in both the United States and Australia. Exploration activities frequently utilize a blend of the aforementioned technologies to assess the distribution and resource potential of subsurface hydrogen.

2.3 | Research Status

It is well established that the formation and accumulation of natural hydrogen are highly dependent on local geological characteristics, with significant regional differences in resource occurrence and potential manifesting as distinct types of geological hydrogen terranes—varying, for instance, in tectonic settings, rock types, and composition—as outlined in ref. [10] on hydrogen accumulation. As an emerging clean energy resource, natural hydrogen has attracted great attention worldwide in recent years, and many countries have carried out related development projects, as summarized in Table 1. For a detailed global map categorizing the phases, refer to the supplementary map in Supporting Information S1: Figures S1 and S2.

2.3.1 | Mali, Africa

The exploration and advancement of natural hydrogen resources in Mali, Africa, represented a significant milestone in the worldwide energy transition. In 2012, Hydroma Canada identified hydrogen concentrations of up to 98% in a previously cemented well located in the village of Bourakebougou, Mali [54]. The company utilized the well to establish the inaugural commercial natural hydrogen power facility globally, supplying electricity to the nearby village.

The Bourakebougou project has since demonstrated continuous hydrogen production, with plans to expand power generation capacity to serve additional local communities, though updates on its current operational status remain limited [55].

The above-mentioned finding generated global interest and prompted extensive research into natural hydrogen. The successful development of natural hydrogen in Mali not only

TABLE 1 | A brief summary of the natural hydrogen development projects[a].

Ref.	Country	Location	Developers	Status/progress
[46]	Mali, Africa	Bourakebougou	Hydroma	Demonstrations launched in 2012; current extraction status uncertain
[47]	France	Lorraine basin	La Française d'Énergie	Applied for an exclusive mining exploration permit in 2023
[48]	France	Pyrenees-big Bearn, Western Province district	TBH2 Aquitaine	The French government approved the country's first natural hydrogen exploration plan "Sauve Terre H_2" in early December 2023, with a license validity period of 5 years
[49]	America	Arizona	Desert mountain energy	In 2022, natural hydrogen was discovered in three wells, including a well that drilled to a depth of 1200 m into the granite top
[50]	America	Kansas	Natural hydrogen energy	Exploratory drilling was completed in 2019
[50]	America	Nebraska	HyTerra	The company has raised $337 million in funding since March 2022
[51]	Australia	Yorke peninsula	Gold Hydrogen	Drilling permit granted for exploration from October 2023
[52]	Australia	Eyre Peninsula	H2EX	In June 2022, exploration rights for PEL Block 691 on Eyre Peninsula were acquired. In November 2023, low- impact 3D ambient noise tomography (ANT) was finished
[51]	Australia	Amadeus Basin	Central Petroleum	In 2022, natural H_2 and He gas reservoirs were discovered under the salt dome structure in the Amadeus Basin. Drilled in 2023 in the Dukas, Kitty Mountain, and Magee/Mahler blocks, they have estimated hydrogen resources of 50.8 billion, 5.3 billion, and 600 million cubic feet, respectively
[53]	Spain	Pyrenees	Helios Aragon	Drilling permit granted for exploration from 2024

[a] Due to the nascent stage of natural hydrogen research and limited exploration efforts, precise global quantitative data remain scarce, and most projects lack sufficient genesis data. Natural hydrogen formation may also involve overlapping mechanisms, so corresponding types are not specified here. This table aims to highlight promising regions, with updates to follow as research advances.

demonstrates its potential as a clean, efficient, and carbon-free energy source but also could offer a new solution for industries struggling to decarbonize through electricity.

The exploration and advancement of natural hydrogen can leverage the established expertise and insights gained from oil and gas development. This field holds significant potential for future research and application, particularly concerning genetic mechanisms, resource exploration, potential assessment, and the processes of extraction and utilization. The natural hydrogen development initiative in Mali has showcased its viability for commercialization, garnering international acclaim for its achievements [56].

Natural hydrogen exploration techniques are also evolving rapidly, and remote sensing, geochemical, geophysical, and petrophysical technologies can be used to more effectively detect and assess natural hydrogen resources. The progress in science and technology, coupled with the rising global demand for clean energy, is anticipated to drive a continued growth in research and development activities related to natural hydrogen, positioning it as a crucial element in a sustainable energy future [7].

2.3.2 | France

France is highly engaged in the advancement of natural hydrogen, demonstrating significant progress in both exploration and research, while also exhibiting a strong commitment to policy development and commercialization efforts.

In May 2023, the Française de l'Energie (FDE) discovered highly concentrated natural hydrogen in a well in the Lorraine mining basin, which was considered as one of the largest potential natural hydrogen deposits ever discovered in Europe [47]. Thus, FDE applied for an exclusive mining exploration permit entitled "Trois-Évêchés Permit" to explore for natural hydrogen gas in the Lorraine mining basin covering an area of 2254 square kilometers. Based on the information found on the official website of the FDE, this permit for natural hydrogen exploration is integral to the Group's strategic development within the hydrogen ecosystem of the Greater Region, encompassing Grand Est, Wallonia, Luxembourg, Sarre, and Rhineland-Palatinate. The aim is to deliver locally produced energy that is both ecologically sustainable and economically viable for residents, industries, and communities in these areas, all of which are significant energy consumers. Additionally, this initiative will gain from the upcoming launch of MosaHYc, a project led by GRTgaz and CREOS, which will facilitate the transportation of hydrogen through a cross-border pipeline dedicated entirely to hydrogen.

Beyond the Lorraine basin, the Pyrenees region has emerged as another key focus of natural hydrogen research, with numerous studies documenting its exploration potential [57, 58]. Identified by France's IFPEN as a high-potential area for native hydrogen, the Pyrenees features hydrogen seepage along major faults rooted in mantle rocks, linked to hydrogen generation using serpentinization. Academic and industrial collaborations, such as joint efforts by CNRS, the University of Toulouse, and tech firms, have deployed advanced seismic technologies here to map subsurface hydrogen systems, while exploration permits for the Pyrenean foothills have also been granted to advance resource assessment [59].

The French government attaches great importance to the potential of natural hydrogen, and the French President mentioned in the "France 2030" investment plan that large funds would be allocated to research the potential of natural hydrogen, emphasizing that France is among the nations with the most significant reserves of natural hydrogen, positioning itself to potentially emerge as a leader in the future production of this energy source [60].

2.3.3 | United States

The United States (US) has demonstrated considerable enthusiasm and advancement in the research, exploration, and development of natural hydrogen. The US Department of Energy (DOE) has published the National Clean Hydrogen Strategy and Roadmap, which suggests that the production of clean hydrogen in the United States is expected to rise significantly by 2030, and that clean hydrogen will be pivotal in decreasing carbon emissions across the nation [61].

Recent progress in the exploration and development of natural hydrogen in the US encompasses the successful drilling of the inaugural dedicated hydrogen exploration well, Hoarty NE3, located in Nebraska, along with the identification of hydrogen flow rates [50]. In addition, Koloma, a natural hydrogen startup company in the United States, received venture capital for the research and development of natural hydrogen [62]. The US government has earmarked a substantial amount of funds to foster the development of clean energy and decarbonization technologies, emphasizing the importance of clean energy solutions like natural hydrogen.

The US DOE also launched the "Hydrogen Shot Plan", which aims to significantly reduce the cost of clean hydrogen energy through technological innovation and stimulate private sector investment. Additionally, the US DOE's Advanced Energy Research Projects Agency (ARPA-E) announced funding to launch the "Geohydrogen" program to produce hydrogen from geological layers with minimal economic cost and environmental impact through the development and demonstration of transformative technologies [7]. The US DOE's ARPA-E has further specified that this $20 million funding supports 16 projects under its "Geologic Hydrogen" program, with core focuses including stimulating natural hydrogen production using in situ serpentinization and developing advanced detection technologies—both aligned with the goal of low-cost, low-environmental-impact hydrogen extraction from geological formations [62, 63].

The actions taken by the US government regarding policy and financial backing underscore the significance of natural hydrogen in the future energy landscape. Natural hydrogen research and exploration activities in the US are expected to continue to increase, which will not only help advance the clean energy transition in the US but also potentially have a profound impact on the global hydrogen industry's development.

2.3.4 | Australia

Australia has made remarkable progress in natural hydrogen research and exploration, becoming one of the hotspots of natural hydrogen research in the world. According to the report from the Australian Renewable Energy Agency (ARENA) [64], the Hydrogen Headstart Program has been launched, investing $2 billion to support two to three flagship projects with the aim of achieving up to 1 GW of electrolytic hydrogen production capacity by 2030. This broader investment climate in the hydrogen field may also indirectly benefit the research and exploration of natural hydrogen, as it fosters an environment of innovation and technological advancement relevant to all forms of hydrogen energy.

As for the exploration of natural hydrogen, the Australian company Gold Hydrogen has measured extremely high-purity hydrogen content in Kangaroo Island and the south of the York Peninsula, using natural hydrogen wells, making a major breakthrough in the exploration of natural hydrogen resources in the world [51]. Gold Hydrogen has reported that anomalies with high hydrogen and helium concentrations were also identified in the Ramsay 1 and Ramsay 2 natural hydrogen wells. A concentration of 73.3% natural hydrogen was found 250 m underground. The potential hydrogen and helium resources in the project area were initially estimated at 1.31 million tons and 1.16 billion cubic meters, respectively. In April 2024, another well test at Ramsay 2 measured hydrogen at 95.8% purity at 531 m below ground level and found highly permeable dolomite and limestone formations conducive to future industrial development.

Moreover, the Australian government has allocated a significant amount of funds to facilitate the creation of a hydrogen energy center and an international collaboration initiative focused on locally produced renewable energy and essential minerals. This investment aims to position Australia as a leading global supplier of hydrogen energy while enhancing the country's role in the critical minerals supply chain through the use of domestically sourced clean energy. These initiatives reflect Australia's optimistic stance and robust research and development capabilities in the hydrogen sector. Such progress will not only drive Australia's transition to clean energy but also have a substantial impact on the growth of the global hydrogen industry.

2.3.5 | Spain

Spain is vigorously developing its green hydrogen sector, aiming to become a European supply hub. The government has set a target of 12 GW of electrolyzer capacity for green hydrogen production by 2030, leveraging its abundant renewable resources, including ample sunlight and ideal wind-power coastlines. This strong push into green hydrogen also opens the door to another aspect of the hydrogen energy landscape, in which natural hydrogen could complement Spain's green hydrogen efforts, further strengthening its position in the European hydrogen market.

Spain is also engaged in the research and development of natural hydrogen, because its diverse geology could potentially host natural hydrogen reservoirs. The exploration firm Helios Aragon has identified a hydrogen reservoir in the foothills of the Pyrenees in northern Spain, boasting a capacity exceeding 1 million tonnes. The company intends to drill additional exploration wells in 2024, aiming to commence commercial production by 2028 [7, 53]. The company estimated that the production cost of natural hydrogen could reach 0.75 euros/kg. Given the significant investment in hydrogen-related infrastructure over the recent years, along with ongoing research into regions with potential natural hydrogen reservoirs, these measures show that Spain is actively promoting the development and use of natural hydrogen to achieve its energy transition and carbon neutrality goals.

2.3.6 | China

Amidst the global drive to harness natural hydrogen, China is making significant progress in research and exploration of natural hydrogen. According to the Geological Documentation Center of the China Geological Survey, China has made a major breakthrough in the exploration of natural hydrogen resources. In earlier years, a significant amount of hydrogen was detected in the wells of the Songliao Basin and the Qaidam Basin [65]. These investigations enhance the comprehension of the distribution, reserves, and exploration potential of natural hydrogen in China, thereby offering a scientific foundation for potential commercial development in the future. In 2024, several high concentration hydrogen seeps in the Sanshui basin were discovered by measuring and determining the soil gas content, with the highest soil gas content of 6948 ppm [66]. In the same year, a study of natural hydrogen resources was conducted in Zhangbei County, China [65]. The research identified significant hydrogen anomalies spanning over 1100 square kilometers, characterized by high concentrations of natural hydrogen. These findings offer valuable new perspectives on the development of natural hydrogen resources within China.

As mentioned above, China is making notable progress in natural hydrogen research and exploration, buoyed by robust government support and strategic planning. Our country has established a solid foundation through policies like the “Hydrogen Energy Industry Development Medium- and Long-Term Plan (2021–2035)”, which provides clear guidance for the hydrogen sector.

The China International Hydrogen Congress 2025 indicates that China is increasing its international cooperation in the hydrogen energy sector. Through joint research projects with different countries, it actively participates in global efforts to advance natural hydrogen-related technologies. This cooperation not only promotes knowledge sharing but also contributes to the global development of the natural hydrogen industry. With such combined efforts, China is set to play an increasingly significant role in the global natural hydrogen landscape.

Natural hydrogen is gaining significant global attention as an innovative energy source, with ongoing advancements in the technologies for its exploration and use. Future research will further explore the genetic mechanisms and resource potential of natural hydrogen, thus aiding in the achievement of energy transition and carbon neutrality goals.

3 | Outlook, Impacts and Recommendations

As mentioned above, natural hydrogen is gaining significant recognition as a promising clean energy source within the context of the global energy transition and the pursuit of carbon neutrality. It is anticipated to play a central role in the future of energy transformation. Its large-scale development and use will help reduce the costs of the hydrogen energy industry chain and make hydrogen energy a distinct category of energy. However, the research and commercial advancement of natural hydrogen also encounter various technical challenges and uncertainties that require further research and policy support. As technology advances and costs fall, natural hydrogen is expected to play an increasingly important role in the global energy mix in the future, supporting the realization of a low-carbon or even zero-carbon energy future.

3.1 | Development Prospects

3.1.1 | Resource Potential

The global resource potential for natural hydrogen is immense. As research efforts expand globally, understanding of its reserves continues to advance, indicating the vast, yet-to-be-fully-tapped reserves of natural hydrogen [28].

To assess this potential, current methodologies integrate geological and economic analyses: reserve estimates draw on volumetric calculations (reservoir volume, porosity) and geophysical/well data [67]; resource quality is evaluated using metrics similar to conventionally produced hydrogen—purity (> 99.97% for fuel cells), associated impurities (e.g., methane), plus isotopic signatures (to trace genesis) [68]; economic viability hinges on exploration costs, extraction efficiency, and comparisons with conventional hydrogen [69]. Standardized methodologies remain evolving given the resource's nascent stage.

3.1.2 | Exploration and Development Trajectory

Countries and regions worldwide, including the United States, Canada, Australia, France, and Spain among others, are at the forefront of natural hydrogen exploration and development.

Their active engagement signals a growing global interest in harnessing this resource. A proposed schematic diagram summarizing natural hydrogen exploration stages, technical methods, and corresponding outputs (structured in a tabular format) is provided in Supporting Information S1: Figure S3. Future trends suggest that more nations will join this pursuit, accelerating the discovery and commercialization of natural hydrogen deposits, and fostering a more collaborative international research environment.

3.1.3 | Technological Advancements

Rapid technological progress is set to revolutionize natural hydrogen exploration. The integration of remote sensing technology with geochemical, geophysical, and petrophysical methods will enhance the efficiency and accuracy of resource detection and assessment. Innovations in drilling and extraction techniques are also on the horizon, specifically directional drilling (for targeting deep/hard-to-reach reservoirs) and automated wellbore monitoring [70], enabling safer and more cost-effective access to natural hydrogen reservoirs. Beyond exploration, key innovations will support full-value chain utilization: for storage, high-pressure composite tanks and salt cavern optimization (to cut leakage risks) will boost long-term retention; for transportation, upgrades to existing gas pipelines (for hydrogen blending up to 20%) and dedicated hydrogen pipeline development will lower distribution costs [71]. These advances will further drive the industry forward.

3.1.4 | Cost-Competitiveness

Natural hydrogen has the potential to disrupt the energy market, with promising cost-competitiveness. This cost-advantage positions it as a strong competitor to fossil fuels, making it an attractive option for both energy-intensive industries and power generation. As production scales up and technologies mature, costs are likely to decrease further, enhancing its economic viability and market penetration.

3.1.5 | Infrastructure Integration

Natural hydrogen can be seamlessly integrated into existing energy infrastructures. In the short to medium term, demonstrations of blending natural hydrogen with natural gas and pipeline upgrades are expected to be implemented, facilitating its distribution through existing natural gas networks. Additionally, its compatibility with the processes used for artificially produced hydrogen enables straightforward integration into electricity systems, allowing for efficient energy storage and grid stabilization.

3.1.6 | Diversified Applications

The application scope of natural hydrogen is poised to expand significantly. Beyond traditional energy uses, it is expected to play a crucial role in various industrial sectors. For instance, hydrogen metallurgy offers a low-carbon alternative to conventional metallurgical processes, whereas its use in ammonia production can reduce the industry's carbon footprint. As research progresses, new applications are likely to emerge (e.g., wastewater treatment [72, 73]), further solidifying natural hydrogen's importance across multiple economic sectors. However, at this stage, comparing natural hydrogen with current industrial hydrogen remains difficult as its underground reserves have not been clearly identified, and relevant applications are still in the early stage, resulting in insufficient data to support a systematic comparison; such a comparison will be more meaningful when its reserves are verified and applications further advance in the future.

3.2 | Potential Environmental Impact

3.2.1 | Geological Disruption

Large-scale natural hydrogen exploration and extraction have the potential to compromise geological integrity. Surface and subsurface geological structures, from activities such as drilling and underground well network construction, may be damaged, potentially leading to issues such as ground subsidence and heightened seismic activity. These changes can not only undermine the stability of infrastructure (e.g., oil and gas pipelines or regional highways) but also pose risks to human settlements in the vicinity.

3.2.2 | Climate Change Impacts

Although natural hydrogen is generally regarded as a clean energy source, its extraction process is not without climate-related risks. Methane, a potent greenhouse gas (with a 100-year global warming potential ~28 times that of CO_2) [74], may be released during extraction operations (e.g., drilling, wellhead sealing). In the initial stages of extraction, if methane leakage is not rigorously controlled, its impact on global warming can far exceed that of carbon dioxide [74]. This leakage could offset the environmental benefits associated with using natural hydrogen as an energy alternative and contribute to accelerated climate change.

3.2.3 | Ecosystem Perturbation

The large-scale exploitation of natural hydrogen could significantly disrupt local ecosystems (e.g., grasslands, forest edges in sedimentary basin areas) [75]. Areas earmarked for mining often serve as habitats for diverse wildlife species. The intrusion of extraction activities can lead to habitat destruction, fragmentation, and, ultimately, a decline in biodiversity (e.g., reduced populations of small mammals or pollinators). Disruptions to food chains and ecological balance may have cascading effects on the overall health and resilience of these ecosystems.

3.2.4 | Water-Related Challenges

Natural hydrogen extraction could place substantial demands on water resources, particularly when methods such as hydraulic fracturing are employed—a single fracturing well may consume thousands of cubic meters of water. In regions already facing water scarcity, this increased consumption can exacerbate existing water stress, impacting both human water needs and ecological functions. Moreover, there is a risk of groundwater contamination. Chemicals used in the extraction process or substances mobilized (e.g., fracturing fluid components like guanidines, or heavy metals from rock formations) from geological formations could seep into groundwater, degrading water quality and posing threats to aquatic life and human health.

3.2.5 | Safety and Hazard Risks

Inadequate safety management during natural hydrogen mining operations can induce hydrogen leakage. Given hydrogen's highly flammable nature, with an ignition energy as low as 0.24 mJ, and its explosive concentration range of 4%–75% by volume in air, even small leaks can create significant safety hazards, increasing the risk of fires and explosions. These incidents not only endanger the lives of workers and nearby communities but can also cause environmental damage through the release of pollutants and destruction of surrounding habitats.

3.3 | Recommendations and Remarks

The development and utilization of natural hydrogen resources present a unique opportunity to meet the world's growing energy demands while advancing the global transition towards a low-carbon future. However, this endeavor must be carefully managed to balance the significant economic benefits with the imperative of environmental conservation. The following recommendations outline a strategic approach to maximizing the potential of natural hydrogen while minimizing its negative impacts.

3.3.1 | Rigorous Environmental Impact Assessment

Prior to any natural hydrogen exploration and extraction activities, a comprehensive and in-depth environmental impact assessment (EIA) is needed. This assessment should systematically monitor and analyze various environmental factors, with a particular focus on groundwater levels and water quality. By implementing continuous and detailed monitoring programs, potential environmental risks can be identified at an early stage, allowing for the development of appropriate mitigation strategies. This proactive approach will help safeguard delicate ecosystems, protect water resources, and minimize geological disruptions.

3.3.2 | Robust Safety Management Protocols

Ensuring the safety and reliability of mining technologies is paramount in the natural hydrogen industry. Stringent measures must be implemented to prevent hydrogen leakage, which poses significant risks of fire and explosion. Governments and regulatory bodies should collaborate to develop and enforce strict exploration and mining regulatory frameworks. These frameworks should include regular safety audits, mandatory safety training for all personnel involved in the mining process, and the establishment of emergency response plans. Additionally, enhanced mining supervision, through the use of advanced monitoring technologies and independent inspection teams, will help maintain high safety standards throughout the entire lifecycle of natural hydrogen projects.

3.3.3 | Strengthened International Cooperation

Given the global nature of the natural hydrogen resource and the complex technological challenges associated with its extraction and utilization, international cooperation is essential. Countries should actively engage in knowledge-sharing initiatives, collaborating on research and development efforts to accelerate technological advancements, which also plays a significant role in building a shared future for humanity. By pooling resources and expertise, the global community can collectively address common challenges, such as improving extraction efficiency, reducing costs, and minimizing environmental impacts. International cooperation can also facilitate the standardization of safety and environmental regulations, ensuring a consistent and coherent approach to natural hydrogen development worldwide.

Overall, natural hydrogen has emerged as a highly promising clean energy source, embodying the essence of low-carbon cleanliness and holding the potential to be a linchpin in the global journey towards an energy-sustainable future, thus playing a pivotal role in the ongoing global energy transition. As scientific research progresses and the global demand for clean energy intensifies, the exploration and development of natural hydrogen are expected to expand significantly. However, to realize its full potential, it is crucial to approach its development with a long-term, forward-looking perspective. By implementing the recommendations outlined above, we can ensure that natural hydrogen is harnessed in a manner that maximizes its benefits while protecting the environment and promoting the well-being of current and future generations.

Author Contributions

Yuanming Gao: writing – original draft, writing – review and editing, funding acquisition. **Silin Liu:** writing – review and editing. **Rong Chen:** writing – review and editing. **Zongyi Li:** writing – review and editing. **Xuezhen Wu:** writing – review and editing. **Wen Ma:** writing – review and editing. **Yuzhuo Luo:** writing – review and editing. **Yanhe Wang:** writing – review and editing. **Xi Ding:** writing – review and editing. **Xiaoxin Li:** writing – review and editing. **Henrietta W. Langmi:** writing – review and editing. **Nicholas M. Musyoka:** writing – review and editing. **Lei Jiang:** writing – review and editing. **Rodolfo Christiansen:** writing – review and editing. **Guo-Ming Weng:** writing – original draft, writing – review and editing, supervision, project administration, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Supporting Information S1: ece270026-sup-0001-suppl-data.docx.